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CONTROL OF RESONANT EXCITATION IN PIPING SYSTEMS

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ABSTRACT

Acoustic resonance is a phenomenon which is known to have severe repercussions in a variety of industrial systems. Acoustic resonance can cause high levels of vibrations leading to damage or premature failure of critical components. Although acoustic resonance affects a broad spectrum of industrial equipment, piping systems will be of focus in this work. Both passive and active damping techniques were previously investigated. However, there is a need to investigate the practicality of such devices when implemented in industrial systems. Herschel-Quincke (HQ) tubes have been selected for experimental study throughout this work. The experimental setup consists of an open-air loop pipeline system which is capable of exciting a standing wave with a fundamental frequency of 30 Hz and a target dominant fifth mode of 150 Hz. Transmission loss measurements were performed by means of the two source-location method. Insertion loss measurements were performed with a straight pipe used as the baseline. The current work has shown that Herschel-Quincke devices have potential for practical implementation into resonant piping systems in industry.

NOMENCLATURE

A, B, C & D= Four poles of the aero-acoustic element
c =Speed of sound (m/s)
d= Diameter of HQ side branch (m)
D= Diameter of main pipeline (m)
f_{bpf} = Blade passing frequency (Hz)
h= The ratio of cross-sectional areas for a reactive muffler
IL= Insertion Loss (dB)
k=Wavenumber (1/m)
L_2= Length of main pipeline (m)
L_3= Length of HQ side branch (m)
l=Length of the reactive muffler (m)
M=Mach number
N= Number of impeller blades
ω= Rotational speed of impeller (rpm)
ρ =Density of air (kg/m^3)
S =Cross sectional area of the test section (m^2)
SPL= Sound Pressure Level (dB)
TL = Transmission Loss (dB)
λ= Wavelength (m)

INTRODUCTION

Centrifugal turbomachinery is very commonly used in industry in order to provide flow energy to piping systems. Although they are efficient and cost effective, the centrifugal impeller is well known to act as a sound source. Pressure pulsations are emitted from such machinery according to its blade passing frequency defined in Eq. (1). In most cases, the pressure pulsations will propagate and eventually decay due to the acoustic damping of the system. However, if the acoustic natural frequency of the pipeline system coincides with the blade passing frequency of the turbomachinery then acoustic resonance may occur, a phenomenon which could cause severe damage to the pipeline system and its in-line components [1, 2 & 3]. A particularly critical example had been recently displayed in a nuclear generating station whereby the primary heat transport (PHT) pumps generated pressure pulsations at 150 Hz.

$$f_{bpf} = \frac{N\omega}{2\pi} \tag{1}$$

The fuel channels were in turn acoustically excited due to resonance which lead to end plate failures of the fuel bundle [4]. Although a solution was achieved by shifting the blade passing frequency out of coincidence with the system by changing the number of impeller blades from five to seven, other units are still faced with pressure pulsations of concern. The time and capital cost to overhaul a pump of similar caliber is not always feasible or efficient as the facility may face a production outage lasting several months. Therefore, the current work aims to investigate a passive damping technique to control the resonant excitation in piping systems. Passive damping techniques such as Helmholtz Resonators have been previously investigated in the literature to date [5, 6]. The Herschel-Quincke (HQ) tube will be selected for the current work due to its benefit of geometric simplicity (ease of installation) and because the attention to HQ tubes is notably scarce in the literature, causing the potentially practical device to be overlooked.

The HQ tube is a side branch attachment (a bypass pipe) which connects to the main pipeline at two junctions [7, 8 & 9]. The configuration of the HQ tube is seen in Fig. 1 whereby the length L_3 is a half of a wavelength longer than the length L_2. This difference in path lengths causes a phase shift between the acoustic waves in the main pipeline and the side branch. This destructive interference of waves is the underlying mechanism of the “Type I” attenuation. “Type II” attenuation is due to the inconsistency of area at the two connecting junctions. Reflection of the acoustic wave will cause attenuation at two different

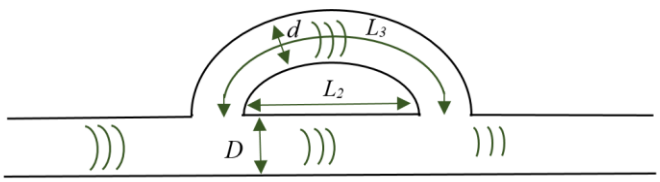

FIGURE 1 - Schematic of a HQ device and its respective parameters

frequencies and thus the HQ tube has a total of three frequencies of attenuation. This work will target the Type-I attenuation peak for use in a resonant pipeline system as the Type-I peak is known to be the most effective mechanism of attenuation with the least effect due to mean flow [10, 11].
Considering that the focus of this work will be to investigate the potential for practical implementation of HQ tubes in piping systems, the experiments are targeted for industrial relevancy.

EXPERIMENTAL SET-UP & METHODOLOGY

The experimental set-up used for acoustic characterization of the various HQ tube configurations is an air loop as shown in Fig. 2. The maximum Mach number achievable in the test section is 0.06 however the current work highlights the no-flow conditions only. The mean flow was driven by a centrifugal air blower and a flow control valve was used in conjunction with a fan flow meter to adjust the flow rate. A flow straightener or bell-mouth was used (depending on the selected direction of flow) in order to reduce turbulence in the test section. To maintain an open end condition and to minimize the noise produced by the air blower, an absorptive muffler was utilized. A loudspeaker was used to excite acoustic resonance in the test section using either a white noise signal with uniformly distributed energy over the frequency spectra or a 150 Hz square wave pulse signal. The fundamental frequency of the piping system is approximately 30 Hz with a targeted fifth mode of 150 Hz. The high order fifth mode of 150 Hz was selected not only for a specific industrial application, but also due to the geometric constraint of a small wavelength corresponding to 150 Hz. The HQ tube was designed with a modular connection to the main pipeline in order to test different locations along the standing wave formed within the test section. Polyethylene pipe was used to manufacture the HQ devices with diameters ranging from 12.7 mm-50.8 mm. The lengths tested were L_3=2.235 m and L_3=3.352 m. The main pipeline test section had a cutoff frequency of approximately 2048 Hz. Two microphone pairs were mounted upstream and downstream of the HQ device so that the two-source location method and transfer matrix method could be employed for the measurement of transmission loss [12, 13]. Each pair of ¼” pressure microphones consisted of a spacing of 196.85 mm corresponding to an upper cut-off frequency of 873 Hz. A data acquisition card samples the data at a frequency of 20 kHz for a time of 90 seconds per trial.

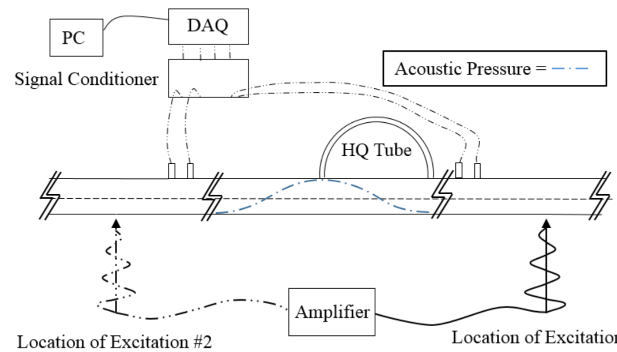

FIGURE 2 - Air loop experimental set-up used for investigation of the HQ device

The two main parameters which are used to characterize the performance of the HQ device during this study are insertion loss and transmission loss. Insertion loss has not been used in previous literature concerning HQ devices due to its dependency on the source and end terminations of the system. For previous research, the focus was primarily on the travelling wave scenario and so insertion loss would not provide any benefit as it captures more than just the effects of the device alone. However, when considering the resonant conditions of a piping system, the end effects of the system must be taken into consideration in order to capture the resonance phenomenon and so insertion loss measurements were considered for the current study. Insertion loss is defined as the difference in the sound pressure level before and after a device is inserted into a system, given by Eq. (2).

$$IL = SPL_{Without\ HQ\ Device} - SPL_{With\ HQ\ Device} \qquad (2)$$

A straight pipe section was used as the base case to compare to the addition of the HQ device. The loud speaker excitation used for insertion loss measurements was a 150 Hz square pulse to mimic the pressure pulsations emitted from an industrial pump during operation.

Transmission loss was conducted in contrary to the purpose of insertion loss as the former is a measurement which is independent of the source and end terminations and will capture the performance of the HQ device exclusively. The two source methodology was used whereby two measurements were performed with the loud speaker in position #1 and position #2 as shown in Fig. 2. The signal used for excitation at the loud speaker is white noise. The transfer matrix of the two straight pipe sections located at the two pairs of microphones were determined and the four poles of the aero-acoustic element located between the two microphone pairs were mathematically obtained from the methodology developed by Munjal [12]. The four poles are used in Eq. (3) to calculate the Transmission loss of the HQ device arrangement within the test section.

$$TL = 20 \cdot log\left(0.5 \cdot \left|A + \frac{S}{\rho c}B + \frac{\rho c}{S}C + D\right|\right) \qquad (3)$$

Transmission loss provides convenience to the current research as it is used in a variety of applications, which open an avenue for validation of the experimental results by means of a reactive muffler. The work of Selamet [14] which provided an analytical model for the transmission loss of a HQ tube was also used as a point of verification.

RESULTS AND DISCUSSION

The experimental methodology for transmission loss was validated by means of a reactive muffler. The measured values of transmission loss were compared with the theoretical predictions from an analytical model stated in Eq. (4) [13] and are shown in Fig. 3. Further comparisons were made between the measured transmission loss of the HQ device to the predictions made by the analytical model developed by Selamet [14]. The overall trend of these additional experiments showed good agreement.

$$TL = 10 \cdot \log\left[1 + 0.25 \cdot \left(h - \frac{1}{h}\right)^2 \cdot sin^2(kl)\right] \qquad (4)$$

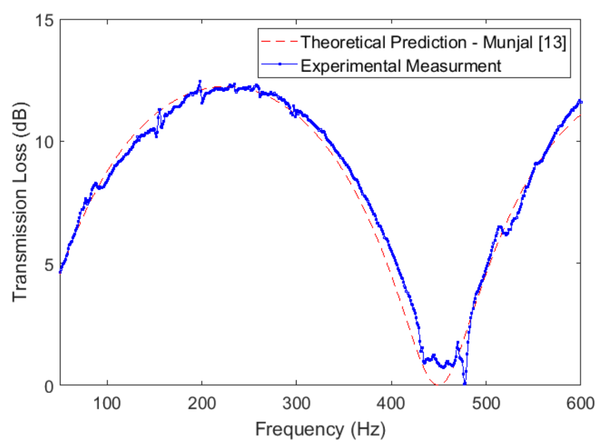

FIGURE 3 – Theoretical and experimental comparison of the transmission loss for a reactive muffler for M=0

When considering insertion loss, which is highly system dependent, it was crucial to confirm that the effect of placing a HQ device on the overall response of the system was minimal at frequencies away from the targeted 150 Hz. Fig. 4 shows the effect of the HQ device on the response of the piping system around the targeted frequency range. It is clear that for small relative diameters, the device has no significant effect on the response of the piping system. However, as the device increases its size relative to the main pipeline, a clear shift in the anti-resonant peaks is evident around the targeted frequency. For this reason, the relative diameter ratios studied in this work will not exceed 0.5. The shift in the anti-resonance peaks is likely due to the increased relative size of the HQ device with respect to the main pipeline causing a more pronounced interaction between the acoustic modes of the HQ device and the main pipeline around the targeted frequency. For the case of d/D=0.25, the volume of the HQ device is a mere 2.5% of the main pipeline and its effect on the natural response is nearly negligible. However, the HQ device with d/D =0.5 yields approximately

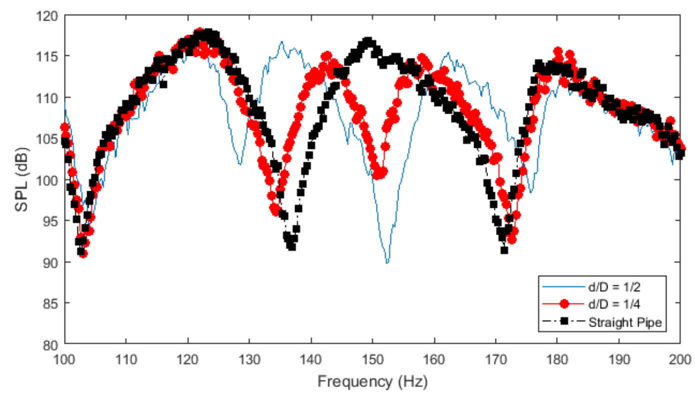

FIGURE 4 - Effects of an HQ device on the natural response of an open-open piping system for M=0

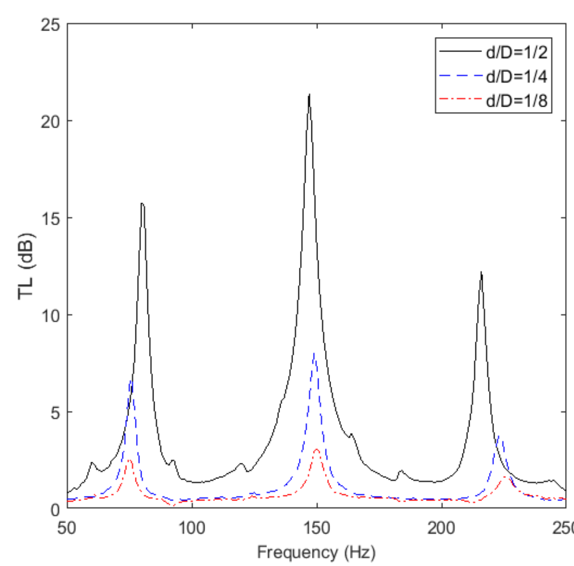

FIGURE 5 - Measured Transmission loss of HQ devices with d/D = 1/2, 1/4 and 1/8 for M=0

10% of the main pipeline volume which has caused a more significant effect on the natural response of the system.

The HQ device was characterized for several relative diameter ratios (ranging from 0.083-0.5) to determine the scalability of the HQ device and to experimentally investigate the normalization scheme utilized in literature. Fig. 5 shows a comparison of the measured transmission loss for various sizes of HQ devices. It is noted that the increase in the relative diameter ratio shows a significant increase in the performance of the device.

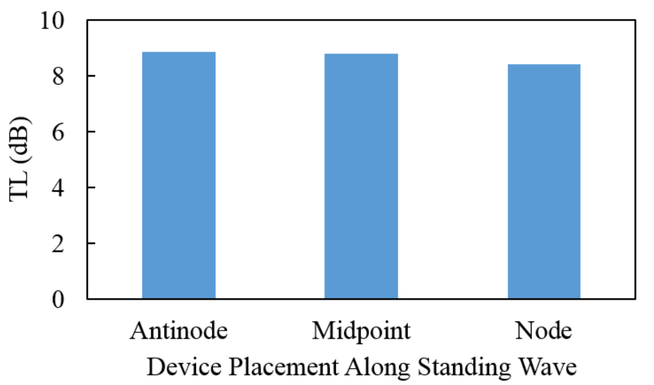

FIGURE 6 - Transmission Loss extracted at the 150 Hz peak for a HQ device of d/D=1/4 placed at various locations along a resonant piping system for M=0

When considering an industrial pipeline system the location along the main pipeline axis for which a damping device is attached needs to be considered. For resonant conditions, the pressure distribution of the pipeline is correlated to the position along the pipeline axis with specific locations of the pressure maximum (antinode) and pressure minimum (node) are known based on the frequency and the acoustic mode which is excited. The current work considers the placement of an HQ device at different locations along a standing wave in order to outline an optimal placement of such a device. Throughout this section of the results transmission loss will not be an effective measurement tool as it does not capture the effects of the end conditions of the system. As illustrated in Fig. 6, it was noted that the transmission loss for an HQ device placed at various locations along a quarter wave length of the pipeline for the frequency of excitation yielded nearly identical attenuation. Moreover, insertion loss must be used in order to compare the performance of the device when placed at various locations along the main pipeline. The antinode denotes the connection of the two junctions of the HQ tube to two consecutive pressure maxima along the main pipeline. A connection of the HQ tube in the antinode position is illustrated in Fig. 2. Conversely, the node denotes the connection of the two junctions of the HQ tube to two consecutive pressure minima. The midpoint denotes connecting the two junctions halfway between the formerly two mentioned positions. Fig. 7 compares the performance of the HQ device when placed at the formerly mentioned locations along the standing wave of the pipeline. It is clearly evident that the pressure maximum of the standing wave is the optimal location of an HQ device for noise attenuation. The type I mechanism observed by the HQ device is seen to be most effective at the pressure antinode location.

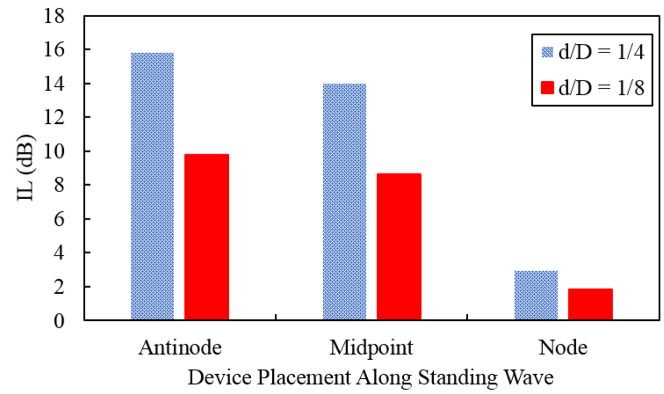

FIGURE 7 - Measured Insertion loss of a HQ device placed at various locations along a resonant piping system for M=0

CONCLUSIONS

The effects of acoustic resonance on industrial pipeline systems have been outlined in this work with a particular focus on a specific problem observed in the nuclear industry. A targeted frequency of 150 Hz was selected for passive damping of a resonant piping system with a fifth mode coinciding with the formerly mentioned frequency. The geometry of the Herschel-Quincke (HQ) tube was tailored to attenuate the frequency of interest using the type I mechanism and measurements were performed in an open air loop to record the insertion loss and transmission loss of the device. The transmission loss of the HQ device was compared to an analytical model and showed a good overall agreement. The transmission loss was utilized to measure the acoustic performance of the device independent of the source and end conditions while insertion loss was required when considering the effects of the resonant system (placement of a HQ device at different positions along the axis of the pipeline). The relative diameter ratio between the HQ tube side branch and the main pipeline was seen to have a significant effect on the attenuation of noise. The trend of relative size of the HQ device to the main pipeline indicates the potential for scalability within a given piping system. When investigating different placements of the HQ device along a quarter wavelength of the standing wave formed within the piping system, the pressure maximum (antinode) was seen to be the optimal location of the device. The maximum pressure condition enhances the Type I mechanism of destructive interference of waves at the downstream junction. Although the Herschel-Quincke tube has received notably less attention in the literature in comparison to other passive damping techniques which have been investigated, it is evident that the practical implementation of HQ tubes show promising results for practical application to resonant piping systems in industry.

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